CHAPTER 3

Plant Nutrients

INTRODUCTION

Plant nutrients can be subdivided into major nutrients and minor or micronutrients. Three of the major nutrients, nitrogen (N), phosphorus (P), and potassium (K), are the most important and are utilized to the greatest extent. These three plant nutrients are the ingredients listed on fertilizers sold at stores. Calcium (Ca), magnesium (Mg), and sulfur (S) are also major nutrients since the plant utilizes them to a greater extent than minor or micronutrients. The micronutrients essential to plant growth are boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn).

It has been recognized for centuries that sewage sludge and biosolids contain plant nutrients. Noer (1926) cited Bruttini (1923), who estimated that the annual excrement of the world's population contains approximately 9 million tons of nitrogen (N) and close to a million tons of phosphoric acid (P_2O_5) and potash (K_2O) that are lost to agriculture. Based on this data, Noer (1926) estimated that the annual loss to the United States is approximately 0.5 million tons of N valued at $180 million, and more than 100,000 tons each of P_2O_5, valued at $12 million, and K_2O, valued at $10 million.

Today this number would be much higher. It is estimated that the U.S. produces approximately 2 million dry tons of sludge and biosolids. This approximates to 10 million wet tons. Assuming an average of 4% nitrogen, the N in sewage sludge and biosolids would amount to about 400,000 tons that could be available to crops. Approximately 250,000 tons of P would be available to crops. In addition, significant quantities of minor elements Ca, Mg, and S would be available. In many cases, soils in the United States are deficient in these nutrients and farmers must add them at significant cost.

In 1977, Sommers obtained data on the nutrient content in 250 sewage sludge samples from 150 wastewater treatment plants. The data on the major plant nutrients, including calcium (Ca), magnesium (Mg), and sulfur (S), are presented in Table 3.1. Nitrogen, P, Ca, and S are present in relatively large amounts, whereas K and Mg are found in much smaller amounts.

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Table 3.1 Concentrations of Total N, P, K, Ca, Mg and S in Sewage Sludge and Biosolids

Plant Nutrient	Sample				
	Type	Number	Range	Median	Mean
Total % N	Anaerobic	85	0.5–17.6	4.2	5.0
	Aerobic	38	0.5–7.6	4.8	4.9
	Other	68	<0.1–10.0	1.8	1.9
	All	191	<0.1–17.6	3.3	3.9
NH_4-N, ppm	Anaerobic	67	120–67,600	1,600	9,400
	Aerobic	33	30–11,300	400	950
	Other	3	5–12,500	80	4,200
	All	103	5–67,600	920	6,540
NO_3-N, ppm	Anaerobic	35	2–4,900	79	520
	Aerobic	8	7–830	180	300
	Other	–	–	–	–
	All	43	2–4,900	170	490
Total % P	Anaerobic	86	0.5–14.3	3.0	3.3
	Aerobic	38	1.1–5.5	2.7	2.9
	Other	65	<0.1–3.3	1.0	1.3
	All	189	<0.1–14.3	2.3	2.5
Total % K	Anaerobic	86	0.02–2.64	0.30	0.52
	Aerobic	37	0.08–1.10	0.38	0.46
	Other	69	0.02–0.87	0.17	0.20
	All	192	0.02–2.64	0.30	0.40
% Ca	Anaerobic	87	1.9–20.0	4.9	5.8
	Aerobic	37	0.6–13.5	3.0	3.3
	Other	69	0.1–25.0	3.4	4.6
	All	193	0.1–25.0	3.9	4.9
% Mg	Anaerobic	87	0.03–1.92	0.48	0.58
	Aerobic	37	0.03–1.10	0.41	0.52
	Other	65	0.03–1.97	0.43	0.50
	All	189	0.03–1.97	0.45	0.54
% S	Anaerobic	19	0.8–1.5	1.1	1.2
	Aerobic	9	1.6–1.1	0.8	0.8
	Other	–	–	–	–
	All	28	0.6–1.5	1.1	1.1

Source: Sommers, 1977, *J. Environ. Qual.* 6: 225–232. With permission.

The nitrogen cycle depicted in Figure 3.1 shows the various transformations that occur when biosolids are applied to land.

When biosolids are incorporated into the soil, the organic matter immediately begins to decompose by the microbes in the soil or those in the biosolids, as long as temperatures are above freezing and there is sufficient moisture. Even at low

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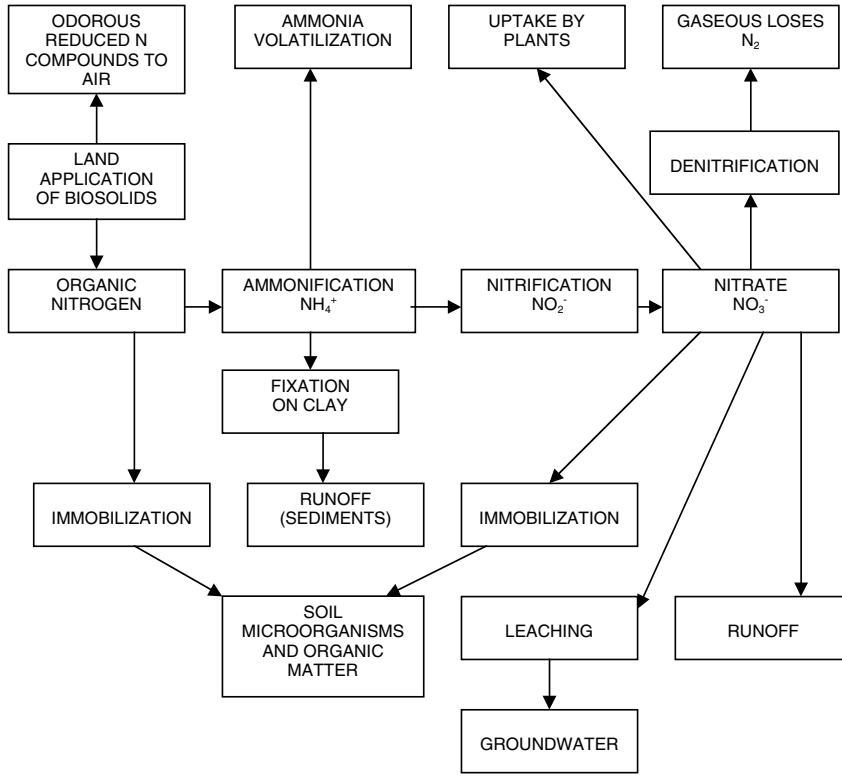

Figure 3.1 The nitrogen cycle when biosolids are applied to land. Many of these conditions are interrelated. (From Epstein et al., 1978, *J. Environ. Qual*. 7: 217–221. With permission.)

temperatures and under drought, decomposition proceeds at a very slow pace as a result of the heat and moisture of the decomposing organisms. Microorganisms utilize the carbon as a source of energy, and the nitrogen for cell development and growth.

The nitrogen components in biosolids are predominantly organic. These have been identified as proteinaceous, amino acids and hexosamines. Parker and Sommers (1983) found that, for anaerobically digested biosolids, organic N ranged from 0.501 to 3.033%. Ammonium nitrogen $(NH_4^+–N)$ ranged from 0.0026 to 0.3760%. Nitrate nitrogen $(NO_3^-–N)$ was extremely low. Their data are summarized in Table 3.2.

NITROGEN

When biosolids are applied to land, the predominantly organic nitrogen undergoes numerous transformations. These transformations are extremely important as they affect plant growth, microbial activity, and reactions through the soil. The transformation of nitrogen in soil resulting from biosolids application is affected by several important conditions in the biosolids and the soil. These include:

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Table 3.2 Carbon and Nitrogen Characteristics of Biosolids

Plant No. and Type of Biosolids	Organic C	Inorganic C	Organic N	Inorganic N NH_4^+	Inorganic N $NO_2^- + NO_3^-$
	%	%	%	µg/g	µg/g
1. Aerobically digested	17.61	0.16	2.519	1360	44
1. Anaerobically digested	18.15	2.06	0.728	590	28
2. Aerobically digested	25.14	0.12	2.346	930	16
3. Aerobically digested	25.32	0.77	3.033	3760	33
4. Aerobically digested	17.47	1.67	1.654	340	1010
5. Anaerobically digested	27.58	1.05	2.744	2010	22
6. Anaerobically digested	11.75	1.87	1.048	56	780
7 Anaerobically digested	21.49	0.75	1.890	1490	120
8. Anaerobically digested	16.72	1.44	1.279	130	18
9. Anaerobically digested	6.78	5.18	0.501	26	90
10. Anaerobically digested	11.97	0.14	1.082	610	2100
11. Anaerobically digested	28.51	0.88	2.006	490	550
12. Anaerobically digested	16.08	0.16	1.692	2440	170
13. Anaerobically digested	15.32	1.66	1.403	630	32

Source: Adapted from Parker and Sommers, 1983.

- Moisture content of soil
- Temperature of soil
- Rate of mineralization
- Oxidation
- Aeration
- Soil porosity
- Biosolids characteristics
- Rate of microbial activity

The nature of the end products depends on the presence or absence of oxygen during the decomposition of the organic N in biosolids. In the presence of oxygen (aerobic conditions) the products are humus-like, nitrogen-containing products that become increasingly resistant to oxidation as decomposition progresses. Ammonia, which is released, can escape into the atmosphere or be converted to nitrites and then to nitrates. In the absence of oxygen (anaerobic conditions) the end products are humus-like materials, ammonia, and nitrogen gas.

Ammonification

Ammonification is the conversion of organic N into ammonium N (NH_4–N) by numerous heterotrophic soil organisms. This form of N is available to plants, but it generally does not leach through the soil, because the positively charged cation (NH_4^+) is held on the surface of negatively charged soil particles. This is termed fixation. Leaching can occur in sandy soils since the cation exchange capacity of these soils is low. NH_4–N attached to soil particles can contaminate surface waters through runoff and erosion.

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Nitrification

Nitrification involves two steps. First NH_4^+ is oxidized to nitrite (NO_2^-) by *Nitrosomonas* spp. bacteria. Then NO_2^- is oxidized to nitrate (NO_3^+) by *Nitrobacter* spp. bacteria. Possibly other species are involved (Tate, 1995). Nitrate is readily available to plants. Nitrite-nitrogen is negatively charged and not adsorbed on soil particles. It thus remains in the soil solution and can be leached below the root zone and percolate into groundwater.

Immobilization

Immobilization is the tying up of nitrogen by soil organisms. When residues high in carbon are incorporated into the soil, the available N is used by the soil microorganisms that decompose the organic matter. Uncured biosolids compost, for example, when incorporated into the soil, will continue to decompose at a fairly high rate and the soil microorganisms will utilize the available N. This can sometimes be evident by yellowing (nitrogen deficiency) of plants. Although the N immobilized as microbial protein is later mineralized during decomposition, it can significantly reduce NO_3^-–N leaching during periods when crop uptake of N is reduced.

Biosolids-applied N may be immobilized into soil organic matter or remain as refractory organic N (Permi and Cornfield, 1969; Ryan et al., 1973).

Denitrification

Denitrification is the biological reduction of NO_3^- or NO_2^- to gaseous forms of N, usually N_2O and N_2. The process is extremely rapid. The predominant bacteria are *Pseudomonas* or *Alcaligenes* (Tate, 1995). Under anaerobic conditions, the nitrogen in the soils is transformed into nitrogen gas and is released to the atmosphere. Since 80% of atmospheric gas consists of N, this addition of N is insignificant. This process primarily occurs in poorly aerated soils and waterlogged soils. After several days of waterlogged soils, much of the NO_3–N is lost by denitrification.

For denitrification to occur, decomposable organic matter must be present. Using liquid anaerobically digested biosolids can result in significant amounts of N losses by denitrification (Kelling et al., 1977). Several studies have indicated that denitrification is a major source of N loss when biosolids are applied (Kelling et al., 1977; Sommers et al., 1979).

Volatilization

When biosolids are applied to the soil surface, some volatilization of ammonia will occur. Any N volatilized is not available to plants or potentially available to be leached and contaminate groundwater. The amount of N volatilized from surface application of biosolids can vary significantly. Numerous studies attempted to evaluate the losses of N from land application of biosolids (Ryan and Keeney, 1975; Terry et al., 1978; Beauchamp, et al., 1978; Adamsen and Sabey, 1987; Robinson

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and Polglase, 2000). These studies indicate that the percentage of NH_4^+ –N can vary from less than 1% to 100%. The majority of N is volatilized during the first few days.

Robinson (1999) reported that when dewatered biosolids were applied in the field, 85% of NH_4^+ –N was lost within the first 3 weeks of application. In a subsequent study, Robinson and Polglase (2000) indicated that majority of NH_4^+ –N was lost during the first week and 71% to 81% was lost during the first 14 days.

Mineralization

Mineralization is the conversion of organic N to inorganic N. Organic N is first converted to NH_4^+ in a process termed ammonification. Then NH_4^+ is oxidized to NO_2^- by *Nitrosomonas* bacteria and NO_2^- is oxidized to NO_3^-. This process is called nitrification.

Thus, mineralization is the combination of ammonification and nitrification, whereby the organic N is converted to NH_4^+ –N and later to NO_3^- –N. The rate-limiting step in soil N mineralization is the conversion of organic N to NH_4^+ –N. Under conditions of adequate aeration and soil moisture and over a broad range of temperatures, the NH_4^+ –N is rapidly oxidized to NO_3^- –N (Stanford and Epstein, 1974).

Knowledge of the rate of nitrogen mineralization is important in determining the rate of biosolids application, potential for crop uptake, and potential for leaching. The amount of N mineralized is a function of several environmental factors and the type of biosolids applied. Chae and Tabatabai (1986) indicated that the rate of N mineralization is dependent on moisture, temperature, C:N ratio, and biosolids properties.

Figure 3.2 shows the rate of nitrogen mineralization for digested biosolids and composted biosolids as related to the amount of N applied per hectare (Epstein et al., 1978). Considerably more N was mineralized from the biosolids (41%) than from the compost (8.5%). The amount of N applied did not affect the percentage mineralized.

Table 3.3 summarizes the data obtained by numerous investigators. The variability shown in this table can be due to the type of biosolids and its condition, as well as the soils used in the studies. The extent of anaerobic or aerobic digestion and the initial N content will affect the organic N mineralization rate. Both composting and alkaline stabilization reduce the amount of N in biosolids, thus reducing the amount of N available for mineralization. Parker and Sommers (1983) indicate that immobilization of N may be a significant process in many soils treated with biosolids. They found that the amount of mineralizable N in biosolids was proportional to the total organic N. The anaerobic digestion or composting of primary, raw or waste activated sludges resulted in reduced organic N levels and decreased the potential amount of mineralizable N.

USEPA and the various states require that the rate of biosolids application be in relation to the crop requirement for nitrogen. This restriction is designed to avoid excess N and prevent leaching to groundwater. Consequently, the transformations that occur in the soil following biosolids application are extremely important. Nitrogen mineralization is the most important transformation since it releases inorganic

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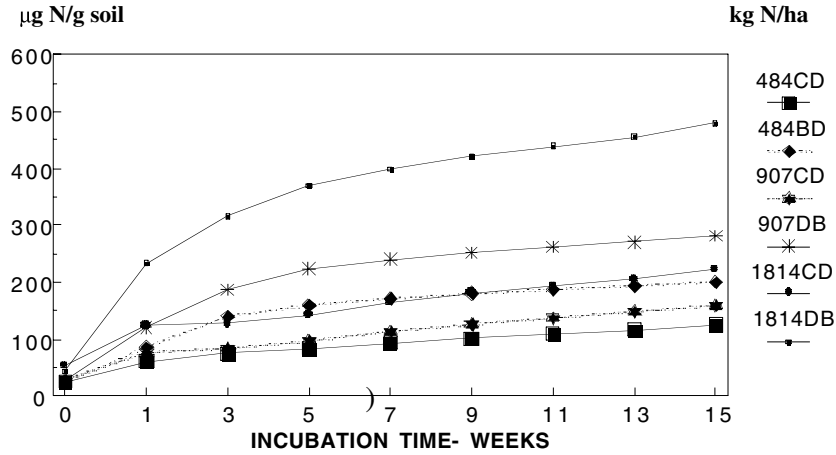

Figure 3.2 Inorganic nitrogen mineralization from digested biosolids (DB) and composted digested (CD) biosolids (From Epstein et al., 1978, *J. Environ. Qual.* 7: 217–221. With permission.)

Table 3.3 Nitrogen Mineralization Rates of Biosolids

Biosolids Type	Incubation Period	Percent Mineralized	Source
Anaerobically digested	16 weeks	4–48	Ryan et al., 1973
Anaerobically digested		36–41	Sabey et al., 1975
Anaerobically digested	13 weeks	14–25	Magdoff and Chromec, 1977
Anaerobically digested	15 weeks	40–42	Epstein et al., 1978
Aerobically digested	17 weeks	54–55	Magdoff and Amadon, 1980
Anaerobically digested	32 weeks	56.4–71.6	Lindmann and Cardenas, 1984
Composted digested	15 weeks	7–9.3	Epstein et al., 1978
Composted digested	54 days	6	Tester et al., 1977

N compounds which either are taken up by plants, immobilized, denitrified, or leached to groundwater. Therefore, it is important to know the potential mineralization rate for a given biosolids in relation to soil and climatic conditions.

PHOSPHORUS

Phosphorus (P) is an essential plant nutrient. It has been indicated that P deficiency is the second most important soil fertility problem throughout the world (Lindsey et al., 1989). However, excessive amounts of P in the soil tend to immobilize other chemical elements such as zinc (Zn) and copper (Cu) that are also essential

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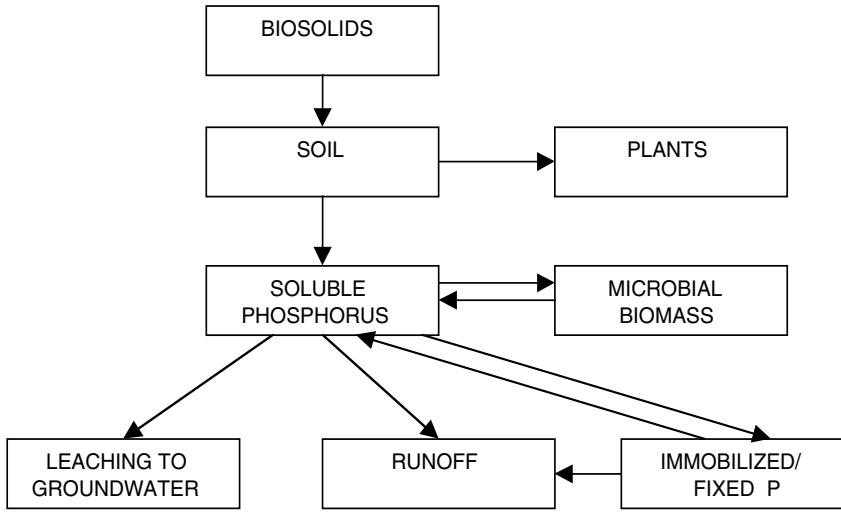

Figure 3.3 The phosphorus cycle when biosolids are applied to land.

for plant growth (Chang et al., 1983). Excessive P in soil can result in nonpoint source pollution of surface waters and shallow ground water (Sims et al., 2000).

Phosphorus in biosolids exists in both organic and inorganic forms. Organic P must undergo mineralization in the soil before plants can take it up. Figure 3.3 shows the P cycle when biosolids are applied to land. Inorganic P is predominant in biosolids. When biosolids are applied at rates consistent with the nitrogen requirement of the crop, excessive P often is applied. Pierzynski (1994) calculated that a biosolid having 13 g/kg plant available N (PAN) and 10 g/kg total P applied to supply 150 kg PAN/ha would also apply 115 kg P/ha. This amounts to approximately three times more than would be typically recommended for corn. Maguire et al. (2000) indicated that adding biosolids at currently recommended rates based on PAN will lead to an accumulation of P in soils. Sui et al. (1999) also concluded that adding biosolids at an application rate based on potentially available N could result in the accumulation of P and potentially be of environmental concern. This accumulation of P can result in eutrophication and potentially impact water bodies through surface runoff, subsurface drainage water, or eroded soil. They applied biosolids at rates of 0, 7.4 and 13.0 Mg dry matter per hectare. After 6 years of continuous application to poplars, total P increased significantly at both the 0 to 5 and 5 to 25 cm depths.

POTASSIUM

Potassium in biosolids is generally low (Table 3.1). Since K compounds in the wastewater are soluble, they generally do not settle in biosolids. When biosolids are

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land applied, the exchangeable form of K is the primary source for plants. This element is essential for plant growth and is in sufficient short supply in the soil to limit crop yield. In plants, it is important in amino acid and protein synthesis and photosynthesis. Excess of K in soil can reduce the uptake of other important cations by plants.

MICRONUTRIENTS

Micronutrients are elements essential to plant growth that are found in trace amounts in soils. Many of these micronutrients, however, can be toxic to humans, animals and plants. Several of them are also among the regulated heavy metals because they can be toxic to humans and animals. The seven micronutrients in biosolids are boron (B), copper (Cu), Iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn). The importance of micronutrients in plant growth and agriculture has been extensively studied. The role of these micronutrients, which are regulated as heavy metals, is discussed in Chapter 4. A major resource for further information is *Micronutrients in Agriculture* (Mortvedt et al., 1991).

Early data by Sommers (1977) show the concentration of micronutrients in sewage sludge and biosolids (see Table 3.4).

Boron has several functions in plants. It is important in cell metabolism, nucleic acid, and plasma membrane function (Römheld and Marschner, 1991). The concentration range between B deficiency and toxicity is very small. Boron may be essential to animals and humans, but its nutritional importance has not been established.

Copper is a regulated heavy metal that is essential to plants, animals, and humans. Its toxicity and essentiality are discussed in Chapter 4. In plants, it is important in many roles including photosynthesis, respiration, enzymes, nodulation in legumes, flowering and senescence, reproductive growth, and seed and fruit yield (Römheld and Marschner, 1991).

Table 3.4 Concentration of Plant Micronutrients in Sewage Sludge and Biosolids

Micronutrient	Number of Samples	Range	Median mg/kg	Mean
Boron	109	4–760	33	77
Copper	205	84–10,400	850	1210
Manganese	143	18–7100	260	380
Molybdenum	29	5–39	30	28
Nickel	165	2–3,520	82	320
Zinc	208	101–27,800	1,740	2790
			Percent	
Iron	165	<0.1–15.3	1.1	1.3

Source: Sommers, 1977, *J. Environ. Qual*. 6: 225–232. With permission.

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Iron is essential to plants, animals, and humans. In plants, it is a component of proteins. It affects photosynthesis, respiration, sulfur reduction, and nitrogen fixation (Römheld and Marschner, 1991).

Manganese is essential to plants and is involved in photosynthesis. It also is important in enzyme functions and reactions. It appears to play key roles in disease resistance and plants' defense mechanisms (Römheld and Marschner, 1991).

Molybdenum is important in nitrogen metabolism of plants. It is contained in enzymes such as nitrate reductase and sulfate reductase as well as nitrogenase, and xanthine dehydrogense. It affects pollen formation, tasseling and development of anthers in corn, flowering delay, and fruit production (Römheld and Marschner, 1991).

Nickel's essentiality to plants is comparatively recent. It is important for certain enzymes such as urease. Brown et al. (1987) showed that Ni was essential for grain viability in barley. Because its essentiality to plants has only recently been discovered, there is little research on its importance in plant growth.

Also essential to plants, zinc is involved in carbohydrate metabolism as well as proteins and auxins. This element is important in stabilization and structural orientation of certain membrane proteins (Römheld and Marschner, 1991). Zinc deficiency has been extensively studied. Many soil areas in the United States are zinc deficient and supplemental Zn is often added to soils.

CONCLUSION

Biosolids can be an important source of plant macro and micronutrients for agricultural or horticultural crops, forestry, and land reclamation. The macronutrients nitrogen and phosphorus can provide the required amounts needed by crops. Potassium, the third most important macronutrient, is low in biosolids, which can also be a source of iron, boron, copper, nickel and other micronutrients essential for plant growth.

Excessive nitrogen or phosphorus applied to soils can be a source of pollution in both ground- and surface water. Nitrogen compounds can move through the soil profile into groundwater resources, and phosphorus and nitrogen in runoff and eroded particles can enter surface waters, resulting in eutrophication.

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